ATTACHMENT 8 – OIL-SPILL REMOTE SENSORS: NEW TOOLS THAT PROVIDE SOLUTIONS TO OLD PROBLEMS, ENVIRONMENT CANADA, 1998

Review of Oil Spill Remote Sensing*

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Abstract

Airborne and space-borne sensors are reviewed and evaluated in terms of their usefulness in responding to oil spills. Recent developments and trends in sensor technology are summarized.

A common passive sensor is an infrared camera or an IR/UV (infrared/ultraviolet) system. The inherent weaknesses include the inability to discriminate oil on beaches, among weeds or debris. Among active sensors, the laser fluorosensor is a most-useful instrument because of its unique capability to identify oil on backgrounds that include water, soil, ice and snow. It is the only sensor that can positively discriminate oil on most backgrounds. Disadvantages include the large size, weight and high cost. Radar, although low in priority for purchase, offers the only potential for large area searches and foul weather remote sensing. Radar is costly, requires a dedicated aircraft, and is prone to many interferences.

Equipment that measures relative slick thickness is still under development. Passive microwave has been studied for several years, but commercial instruments lack sufficient spatial resolution to be practical, operational instruments. A laser-acoustic instrument, which provides the only technology to measure absolute oil thickness, is under development.

Equipment operating in the visible region of the spectrum, such as cameras and scanners, is useful for documentation or providing a basis for the overlay of other data. It is not useful beyond this because oil shows no spectral characteristics in the visible region which can be used to discriminate oil.

Introduction

Large spills of oil and related petroleum products in the marine environment can have serious biological and economic impacts. Public and media scrutiny is usually intense following a spill, with demands that the location and extent of the oil spill be identified. Remote sensing is playing an increasingly important role in oil spill response efforts. Through the use of modern remote sensing instrumentation, oil can be monitored on the open ocean around the clock. With a knowledge of slick locations and movement, response personnel can more effectively plan countermeasures in an effort to lessen the effects of the pollution.

Even though sensor design and electronics are becoming increasingly sophisticated and much less expensive, the operational use of remote sensing equipment lags behind the technology. In remote sensing, a sensor, other than the eye or conventional photography, is used to detect the target of interest at a distance. The most common forms of oil spill surveillance and mapping are done with simple still or video photography. Remote sensing from an aircraft is still the most common form of oil spill tracking. Attempts to use satellite remote sensing for oil spills continue, although success is not necessarily as claimed and is generally limited to identifying

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features at sites where known oil spills have occurred.

Several general reviews of oil spill remote sensing have been prepared (Fingas and Brown 2000). These reviews show that there is progress in oil spill remote sensing, however that this progress is slow. Furthermore these reviews show that specialized sensors offer advantages to oil spill remote sensing. Generic, off-the-shelf sensors have very limited application to oil spills.

Optical Sensors

Visible

The use of human vision alone is not considered remote sensing, however still forms the most common technique for oil spill surveillance. In the past, major campaigns using only human vision were mounted with varying degrees of success (Taft et al. 1995). Optical techniques are the most common means of remote sensing. Cameras, both still and video, are common because of their low price. In recent years, visual or camera observation has been enhanced by the use of GPS (Global Positioning Systems) (Lehr 1994). Direct annotation of video images with GPS information is possible and provides useful documentation.

In the visible region of the electromagnetic spectrum (approximately 400 to 700 nm), oil has a higher surface reflectance than water, but also shows limited nonspecific absorption tendencies. Oil generally manifests throughout this visible spectrum. Sheen shows up silvery and reflects light over a wide spectral region down to the blue. As there is no strong infomation in the 500 to 600 nm region, this region is often filtered out to improve contrast (O'Neil et al. 1983). Overall, however, oil has no specific characteristics that distinguish it from the background (Brown et al. 1996). Taylor studied oil spectra in the laboratory and the field and observed flat spectra with no useable features distinguishing it from the background (Taylor 1992). Therefore, techniques that separate specific spectral regions do not increase detection capability. It has been found that high contrast in visible imagery can be achieved by setting the camera at the Brewster angle (53 degrees from vertical) and using a horizontally aligned polarizing filter which passes only that light reflected from the water surface. This is the component that contains the information on surface oil (O'Neil et al. 1983). It has been reported that this technique increases contrast by up to 100%. Filters with band-pass below 450 nm can also be used to improve contrast.

On land, hyperspectral data has been used to delineate the extent of an oil well blowout (Bianchi et al. 1995). The technique used was spectral reflectance in the various channels as well as the usual black coloration.

Video cameras are often used in conjunction with filters to improve the contrast, in a manner similar to that noted for still cameras. This technique has had limited success for oil spill remote sensing because of poor contrast and lack of positive discrimination. Despite this, video systems have been proposed as remote sensing systems (Bagheri et al., 1995). With new light-enhancement technology (low lux), video cameras can be operated even in darkness.

Scanners were often used as sensors in the visible region of the spectrum. A rotating mirror or prism sweeps the field-of-view (FOV) and directs the light towards a detector. Before the advent of CCD (charge-coupled device) detectors, this sensor provided much more sensitivity and selectivity than a video camera. Another advantage of scanners is that signals can be digitized and processed before display. Recently, newer technology has evolved and similar digitization can be achieved without scanning by using a CCD imager and continually recording all elements, each of which is directed to a different field-of-view on the ground. This type of sensor, known as a push-broom scanner, has many advantages over the older scanning types. It can overcome several types of aberrations and errors, the units are more reliable than mechanical ones, and all data are collected simultaneously for a given line perpendicular to the direction of the aircraft's flight. Several types of scanners have been developed recently. In Canada, the MEIS (Multi-detector Electro-optical Imaging Scanner)(O'Neil et al. 1983) and the CASI (Compact Airborne Spectrographic Imager) (Palmer et al. 1994) have been developed, and in Holland, the Caesar system was developed (Wadsworth et al. 1992).

The use of visible techniques in oil spill remote sensing is largely restricted to documentation of the spill because there is no mechanism for positive oil detection. Furthermore, there are many interferences or false alarms. Sun glint and wind sheens can be mistaken for oil sheens. Biogenic material such as surface weeds or sunken kelp beds can be mistaken for oil. Oil on shorelines is difficult to identify positively because weeds look similar to oil and oil cannot be detected on darker shorelines. In summary, the usefulness of the visible spectrum for oil detection is limited. It is, however, an economical way to document spills and provide baseline data on shorelines or relative positions.

Infrared

Oil, which is optically thick, absorbs solar radiation and re-emits a portion of this radiation as thermal energy, primarily in the 8 to 14 μm region. In infrared (IR) images, thick oil appears hot, intermediate thicknesses of oil appear cool, and thin oil or sheens are not detected. The thicknesses at which these transitions occur are not known, but evidence indicates that the transition between the hot and cold layer lies between 50 and 150 μm and the minimum detectable layer is between 20 and 70 μm (Fingas et al., 1998; Goodman 1989: Hurfurd 1989; Neville et al. 1979). The reason for the appearance of the "cool" slick is not fully understood. The most plausible theory is that a moderately thin layer of oil on the water surface causes destructive interference of the thermal radiation waves emitted by the water, thereby reducing the amount of thermal radiation emitted by the water.

Infrared devices can not detect emulsions (water-in-oil emulsions) under most circumstances (Bolus 1996). This is probably a result of the high thermal conductivity of emulsions as they typically contain 70% water and thus do not show a temperature difference.

Infrared cameras are now very common and commercial units are available from several manufacturers. In the recent past, scanners with infrared detectors were largely used. A disadvantage of any type of infrared detector, however, is that they require cooling to avoid thermal noise, which would overwhelm any useful signal. Liquid nitrogen, which provides about four hours of service, has traditionally been used to cool the detector. New, smaller sensors use closed-cycle or Joule-Thompson coolers which operate on the cooling effect created by expanding gas. While a gas cylinder or compressor must be transported with this type of cooler, refills or servicing may not be required for days at a time (Goodman 1988). Many new detection arrays require no cooling.

Most infrared sensing of oil spills takes place in the thermal infrared at wavelengths of 8 to 14 μm. One sensor, which is designed as a fixed-mounted unit, uses the differential reflectance of oil and water at 2.5 and 3.1 μm (Seakem 1988). Tests of a mid-band IR system (3.4 to 5.4 μm) over the TENYO MARU oil spill showed no detection in this range, however, ship scars were visible (Rogne and Smith 1992: Rogne et al. 1992b; Kennicutt et al. 1992).

Specific studies in the thermal infrared (8 to 14 µm) show that there is no spectral structure in this region (Salisbury et al. 1993). Tests of a number of infrared systems show that spatial resolution is extremely important when the oil is distributed in windrows and patches, emulsions are not always visible in the IR, and cameras operating in the 3 to 5 µm range are only marginally useful (Hover 1994).

Table 1 shows the new focal plane detectors and some of the cameras built with these sensors. The developments in this technology are very rapid at this time.

Table 1 **Examples of New Infrared Sensors and Cameras**

Focal Plane Arrays						**Commercial Cameras**	
Technology	**Manufacturer**	**Sub-Designation**	**Wave-Length**	**Array Size**	**Cooling**	**Manufacturer**	**Model**
Si:As	Boeing	BIB	2 to 28µm	128 X 128			
				256 X 256			
	SBRC	IBC	2 to 28µm	320 X 240			
						Infrared Laboratories (all of above sensors)	
Silicon Microbolometer							
	Boeing	U3000	8 to 14µm	320X240	uncooled	Texas Infrared	Spectrum R/M
	Raytheon		8 to 14µm	320 X 240	uncooled		
In Sb	SBFP - Lockheed Martin		7.5 to 14µm	327 X 245	uncooled	Lockheed Martin	LTC500
HgCdTe	Raytheon		9 to 11µm	128 X 128	Dewar	Raytheon Amber	
			8.5 to 11 µm	256 X 256	Dewar	Raytheon Amber	

The relative thickness information in the thermal infrared can be used to direct skimmers and other countermeasures equipment to thicker portions of the slick. Oil detection in the infrared is not positive, however, as several false targets can interfere, including weeds, shoreline, and oceanic fronts. Infrared is reasonably inexpensive, however, and is currently the prime tool used by the spill remote sensor operator.

Ultraviolet

Ultraviolet sensors can be used to map sheens of oil as oil slicks display high reflectivity of ultraviolet (UV) radiation even at thin layers (<0.01 µm). Overlaid ultraviolet and infrared images are often used to produce a relative thickness map of oil spills. Ultraviolet cameras, although inexpensive, are not often used in this process, however, as it is difficult to overlay camera images (Goodman 1988). Data from infrared scanners and that derived from push-broom scanners can be easily superimposed to produce these IR/UV overlay maps. Ultraviolet data are also subject to many interferences or false images such as wind slicks, sun glints, and biogenic material. Since these interferences are often different than those for infrared sensing, combining IR and UV can provide a more positive indication of oil than using either technique alone.

Laser Fluorosensors

Laser fluorosensors are active sensors that take advantage of the fact that certain compounds in petroleum oils absorb ultraviolet light and become electronically excited. This excitation is rapidly removed through the process of fluorescence emission, primarily in the visible region of the spectrum. Since very few other compounds show this tendency, fluorescence is a strong indication of the presence of oil. Natural fluorescing substances, such as chlorophyll, fluoresce at sufficiently different wavelengths than oil to avoid confusion. As different types of oil yield slightly different fluorescent intensities and spectral signatures, it is possible to differentiate between classes of oil under ideal conditions (Brown et al. 2000a; Hengsterman and Reuter 1990; Balick et al. 1997).

Most laser fluorosensors used for oil spill detection employ a laser operating in the ultraviolet region of 300 to 355 nm (Diebel et al. 1989; Geraci et al. 1993). With this wavelength of activation, there exists a broad range of fluorescent response for organic matter, centered at 420 nm. This is referred to as Gelbstoff or yellow matter, which can be easily annulled. Chlorophyll yields a sharp peak at 685 nm. The fluorescent response of crude oil ranges from 400 to 650 nm with peak centers in the 480 nm region. The use of laser fluorosensors for chlorophyll and other applications has been well documented (Pantani et al. 1995). One laser fluorosensor operating at 488 nm from an Argon laser, was successful in detecting oil from a ship platform (Campbell and McStay 1995).

Another phenomenon, known as Raman scattering, involves energy transfer between the incident light and the water molecules. The water molecules absorb some of the energy as rotational-vibrational energy and return the light as the incident energy, less this energy of rotation or vibration. The Raman signal for water occurs at 344 nm when the incident wavelength is 308 nm (XeCl laser). The water Raman signal is useful for maintaining wavelength calibration of the fluorosensor in operation, but has also been used in a limited way to estimate oil thickness, because the strong absorption by oil on the surface will suppress the water Raman signal in proportion to thickness (Hoge and Swift 1980; Piskozub et al. 1997). The point at which the Raman signal is entirely suppressed depends on the type of oil, since each oil has a different absorption strength.

The principle of fluorescence can also be used on a smaller scale. A hand-held UV light has been developed to detect oil spills at night at short range (Fingas 1982). Another related instrument is the "Fraunhofer Line Discriminator" which is essentially a passive fluorosensor using solar irradiance instead of laser light (O'Neil et al. 1983). This instrument was not very successful because of the limited discrimination and the low signal-to-noise ratio.

Laser fluorosensors have significant potential as they may be the only means to discriminate between oiled and unoiled weeds and to detect oil on different types of beaches. Tests on shorelines show that this technique has been very successful (Dick et al. 1992). Algorithms for the detection of oil on shorelines have been developed (James and Dick 1996). The fluorosensor is also the only reliable means of detecting oil in certain ice and snow situations. Recent tests and usage shows that the laser fluorosensor is a powerful tool for oil spill remote sensing (Brown et al. 2000a)

Microwave Sensors

Radiometers

The ocean emits microwave radiation. Oil on the ocean emits stronger microwave radiation than the water and thus appears as a bright object on a darker sea. The emissivity factor of water is 0.4 compared to 0.8 for oil (O'Neil et al. 1983; Ulaby et al. 1989). A passive device can detect this difference in emissivity and could therefore be used to detect oil. In addition, as the signal changes with thickness, in theory, the device could be used to measure thickness.

This detection method has not been very successful in the field, however, as several environmental and oil-specific parameters must be known. In addition, the signal return is dependent on oil thickness but in a cyclical fashion. A given signal strength can imply any one of two or three signal film thicknesses within a given slick. Microwave energy emission is greatest when the effective thickness of the oil equals an odd multiple of one quarter of the wavelength of the observed energy. Biogenic materials also interfere and the signal-to-noise ratio is low. In addition, it is difficult to achieve high spatial resolution (Goodman 1994a).

The Swedish Space agency has done some work with different systems, including a dual band, 22.4- and 31-GHz device, and a single band 37-GHz device (Fast 1986). Skou, Sorensen and Poulson describe a 2-channel device operating at 37.5 and 10.7 GHz (Skou et al 1994). Mussetto and co-workers at TRW described the tests of 44-94-GHz and 94-154-GHz, 2-channel devices over oil slicks (Mussetto et al. 1994). They showed that correlation with slick thickness is poor and suggest that factors other than thickness also change surface brightness. They also suggest that a single-channel device might be useful as an all-weather, relative-thickness instrument. Tests of single-channel devices over oil slicks have also been described in the literature, specifically a 36-GHz (Zhifu and Wiesbeck 1988) and a 90-GHz device (Süss et al. 1989). A new method of microwave radiometry has recently been developed in which the polarization contrasts at two orthogonal polarizations are measured in an attempt to measure oil slick thickness (Pelyushenko 1995; 1997). A series of frequency-scanning radiometers have been built and appear to have overcome the difficulties with the cyclical behaviour (McMahon et al. 1997).

In summary, passive microwave radiometers may have potential as all-weather oil sensors. Their potential as a reliable device for measuring slick thickness, however, is uncertain at this time.

Radar

Capillary waves on the ocean reflect radar energy, producing a "bright" image known as sea clutter. Since oil on the sea surface dampens some of these capillary waves, the presence of an oil slick can be detected as a "dark" sea or one with an absence of this sea clutter. Unfortunately, oil slicks are not the only phenomena that are detected in this way. There are many interferences or false targets, including fresh water slicks, wind slicks (calms), wave shadows behind land or structures, weed beds that calm the water just above them, glacial flour, biogenic oils, and whale and fish sperm (Frysinger et al. 1992; Alpers and Hühnerfuss 1987; Poitevin and Khaif 1992; Hühnerfuss et al. 1989). As a result, radar can be ineffective in locations such as Prince William Sound, Alaska where dozens of islands, fresh water inflows, ice, and other features produce hundreds of such false targets. Despite these limitations, radar is an important tool for oil spill remote sensing because it is the only sensor that can be used for searches of large areas and it is one of the few sensors that can "see" at night and through clouds or fog.

The two basic types of radar that can be used to detect oil spills and for environmental remote sensing in general are Synthetic Aperture Radar (SAR) and Side-Looking Airborne Radar (SLAR). The latter is an older, but less expensive technology, which uses a long antenna to achieve spatial resolution. Synthetic aperture radar uses the forward motion of the aircraft to synthesize a very long antenna, thereby achieving very good spatial resolution, which is independent of range, at the expense of sophisticated electronic processing. While inherently more expensive, the SAR has greater range and resolution than the SLAR. In fact, comparative tests show that SAR is vastly superior (Mastin et al. 1994). Search radar systems, such as those frequently used by the military, cannot be used for oil spills as they usually remove the clutter signal, which is the primary signal of interest. Furthermore, the signal processing of this type of radar is optimized to pinpoint small, hard objects, such as periscopes. This signal processing is very detrimental to oil spill detection.

Experimental work on oil spills has shown that X-band radar yields better data than L- or C- band radar (Intera 1984; C-CORE 1981). It has also been shown that vertical antenna polarizations for both transmission and reception (V,V) yield better results than other configurations (Bartsh et al. 1987; Macklin 1992; Kozu et al. 1987, Madsen et al. 1994). Radar is also limited by sea state. Sea states that are too low will not produce enough sea clutter in the surrounding sea to contrast to the oil and very high seas will scatter radar sufficiently to block detection inside the troughs. Indications are that minimum wind speeds of 1.5 m/s (~3 knots) are required to allow detectability and a maximum wind speed of 6 m/s (~12 knots) will again remove the effect (Hühnerfuss et al. 1996; Hielm 1989). This limits the environmental window of application of radar for detecting oil slicks. Gade et al. (1996) studied the difference between extensive systems from a space-borne mission and a helicopter-borne system. They found that at high winds, it was not possible to discriminate biogenic slicks from oil. At low wind speeds, it was found that images in the L-band showed discrimination. Under these conditions the biogenic material showed greater damping behaviour in the L-band. Okamoto et al. (1996) studied the use of ERS-1 using an artificial oil (oleyl alcohol) and found that an image was detected at a wind speed of 11m/s, but not at 13.7 m/s.

Radar has also been used to measure currents and predict oil spill movements by observing frontal movements (Forget and Brochu 1996). Recently, work has shown that frontal currents and other features can be detected by SAR (Marmorino et al. 1997).

Shipborne radar has similar limitations and the additional handicap of low altitude, which restricts its range to between 8 to 30 km, depending on the height of the antenna. Ship radars can be adjusted to reduce the effect of sea clutter de-enhancement. Shipborne radar successfully detected a surface slick in the Baltic Sea from 8 km away and during a trial off the coast of Canada at a maximum range of 17 km (Tennyson 1985). The technique is very limited by sea state, however, and in all cases where it was used, the presence and location of the slick were already known.

In summary, radar optimized for oil spills is useful in oil spill remote sensing, particularly for searches of large areas and for night-time or foul weather work. The technique is highly prone to false targets, however, and is limited to a narrow range of wind speeds.

Scatterometers

A microwave scatterometer is a device that measures the scattering of microwave or radar energy by a target. The presence of oil reduces the scattering of the microwave signals just as it does for radar sensors, however, and this device is adversely affected by the same large number of false targets. One radar scatterometer was flown over several oil slicks and used a low-power transmitter operating in the Ku band (13.3 GHz) (O'Neil et al. 1983). The "Heliscat", a device with five frequencies has been used to investigate capillary wave damping (Hühnerfuss et al. 1996). The advantage of a microwave scatterometer is that it has an aerial coverage similar to optical sensors and it operates in a nadir geometry, i.e., it looks straight down. The main disadvantages include the lack of discrimination for oil and the lack of imaging capability.

Slick Thickness Sensors

There has long been a need to measure oil slick thickness, both within the oil spill response community and among academics in the field. There are presently no reliable methods, either in the laboratory or the field, for accurately measuring oil-on-water slick thickness. The ability to do so would significantly increase understanding of the dynamics of oil spreading and behaviour. Knowledge of slick thickness would make it possible to determine the effectiveness of certain oil spill countermeasures including dispersant application and in-situ burning. Indeed, the effectiveness of individual dispersants could be determined quantitatively if the oil remaining on the water surface following dispersant application could be accurately measured (Goodman and Fingas 1988).

Finally, there is a need to calibrate some of the more economical and readily available pieces of remote sensing equipment. Several of these sensors provide relative indications of slick thickness, i.e., whether the slick is thick or thin. Calibration of these wide field-of-view sensors would provide a reliable method of estimating the volume of rogue oil slicks. Present airborne surveillance of slicks often results in erroneous estimates of oil quantity.

The suppression of the water Raman peak in laser fluorosensor data discussed in that section has not been fully exploited or tested. This technique may work for thin slicks, but not necessarily for thick ones, at least not with a single excitation frequency. Attempts have been made to calibrate the thickness appearance of infrared imagery, but also without success. It is suspected that the temperatures of the slick as seen in the IR are highly dependent on oil type, sun angle, and weather conditions. If so, it may not be possible to use IR as a calibrated tool for measuring thickness. As accurate surface methods do not exist, it is very difficult to calibrate existing equipment (Brown and Goodman 1986). The use of sorbent techniques to measure surface thickness yields highly variable results (Goodman and Fingas 1988). As noted in the section on microwave radiometers, the signal strength measured by these instruments can imply one of several thicknesses. This methodology does not appear to have potential, other than for measuring relative oil thickness.

A variety of electrical, optical, and acoustic techniques for measuring oil thickness has been investigated (Reimer and Rossiter 1987; Goodman et al. 1997). Two promising techniques were pursued in a series of laboratory measurements. In the first technique, known as "thermal mapping" (Aussel and Monchalin 1989), a laser is used to heat a region of oil and the resultant temperature profiles created over a small region near this heating are examined using an infrared camera. The temperature profiles created are dependent on the oil thickness. A more promising technique involves laser acoustics (Krapez and Cielo 1992; Choquet et al. 1993). The Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor consists of three lasers, one of which is coupled to an interferometer to accurately measure oil thickness (Choquet et al. 1993; Brown et al. 2000b). The sensing process is initiated with a thermal pulse created in the oil layer by the absorption of a powerful CO_2 laser pulse. Rapid thermal expansion of the oil occurs near the surface where the laser beam was absorbed, which causes a step-like rise of the sample surface as well as an acoustic pulse of high frequency and large bandwidth (~ 15 MHz for oil). The acoustic pulse travels down through the oil until it reaches the oil-water interface where it is partially transmitted and partially reflected back towards the oil-air interface, where it slightly displaces the oil's surface. The time required for the acoustic pulse to travel through the oil and back to the surface again is a function of the thickness and the acoustic velocity of the oil. The displacement of the surface is measured by a second laser probe beam aimed at the surface.

Motion of the surface induces a phase or frequency shift (Doppler shift) in the reflected probe beam. This phase or frequency modulation of the probe beam can then be demodulated with an interferometer (Monchalin 1986). The thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil slick. This is a very reliable means of studying oil thickness and has great potential. This technology is being researched by a consortium of agencies including Imperial Oil, Environment Canada, and the United States Minerals Management Service. Laboratory tests have confirmed the viability of the method and a test unit will be flown to confirm its operability.

Acoustic Systems

Pogorzelski (1995) has shown that acoustic means can be used to measure oil viscosities on the surface. A directional acoustic system employing high-frequency forward specular scattering was used in the laboratory and at sea. Signals scattered are related to the rheological film properties. It is not known at this time if the system is scalable or exactly what the limitations are.

Satellite Remote Sensing

Recently, it has been strongly suggested that satellite remote sensing could replace airborne remote sensing. However, current technologies do not support this claim. The use of satellite remote sensing for oil spills has been attempted several times. The slick from the IXTOC I well blowout in Mexico was detected using GOES (Geostationary Operational Environmental Satellite) and also by the AVHRR (Advanced Very High Resolution Radiometer) on the LANDSAT satellite (O'Neil et al. 1983). A blowout in the Persian Gulf was subsequently detected. The massive EXXON VALDEZ slick was detected on SPOT (Satellite Pour l'Observation de la Terre) satellite data (Dean et al. 1990). Oiled ice in Gabarus Bay resulting from the KURDISTAN spill was detected using LANDSAT data (Dawe et al. 1981; Alfoldi and Prout 1982). Several workers were able to detect the Arabian Gulf War Spill in 1991 (Cross 1982; Rand et al. 1992; Al-Ghunaim et al. 1992; Al-Hinai 1993). The HAVEN spill near Italy was also monitored by satellite (Cecamore et al. 1992). A spill in the Barents sea was tracked using an IR band on NOAA 10 (Voloshimo and Sochnev 1992). It is significant to note that, in all these cases, the position of the oil was known and data had to be processed to actually see the oil, which usually took several weeks.

There are several problems associated with relying on satellites for oil spill remote sensing. The first is the timing and frequency of overpasses (Clark 1989) and the absolute need for clear skies to perform optical work. The chances of the overpass and the clear skies occurring at the same time give a very low probability of seeing a spill on a satellite image. This point is well illustrated in the case of the EXXON VALDEZ spill (Noerager and Goodman 1991). Although the spill covered vast amounts of ocean for over a month, there was only one clear day that coincided with a satellite overpass, and that was on April 7, 1989. Another disadvantage of satellite remote sensing is the difficulty in developing algorithms to highlight the oil slicks and the long time required to do so. For the EXXON VALDEZ spill, it took over two months before the first group managed to "see" the oil slick in the satellite imagery, although its location was precisely known.

Several 'automatic' systems have been designed for slick detection (Solberg and Theophilopoulos 1997). Limited testing with ERS-1 has shown that many false signals are present in most locations (Wahl et al. 1993; Bern et al. 1993). Extensive effort on data processing appears to improve the chances of oil detection (Yan and Clemente-Colon 1997)

In its present state, optical satellite imagery does not offer much potential for oil spill remote sensing. Radar satellites, including ERS-1 and -2, Radarsat, and JERS-1, have been useful for mapping known large offshore spills. Radarsat has been used for detecting oil seeps (Biegert et al. 1997) and smaller spills resulting from an oil barge (Werle et al. 1997). The relative location of these smaller slicks was known before the detection. A novel application of Radarsat has been the study of oil lakes in the deserts of Kuwait (Kwarteng et al., 1997). All satellite data suffer from problems of resolution and timeliness. A comparison of the use of satellite- versus airborne-derived data showed that satellite data lacks resolution and timeliness for many oil spill applications (Fingas and Brown 1997).

Real-Time Displays and Printers

A very important aspect of remote sensing is the production of data so that operations people can quickly and directly use it. Real-time displays are important so that remote sensor operators can adjust instruments directly in flight and provide information quickly on the location or state of the spill. A major concern of the client is that data be rapidly available (Goodman 1994b). At this time, existing hardware and software must be adapted as commercial off-the-shelf) equipment for directly outputting and printing sensor data is not yet available.

Future Trends

Advances in sensor technology will continue to drive the use of remote sensors as operational oil spill response tools in the future. Thermal infrared detectors that offer high sensitivity without the need for cooling are just now appearing in the marketplace. This improvement not only reduces the size and complexity of the sensor, but also the cost. In the next decade, advances in solid-state laser technology, in particular diode-pumped solid-state lasers, will greatly reduce the size and energy consumption of laser-based remote sensors. This will promote the use of these sensors in smaller, more economical aircraft within the budget of many more regulatory agencies and maritime countries. Rapidly improving computer capabilities will allow for true real-time processing. At the present time and for the foreseeable future, there is no single “Magic Bullet” sensor that will provide all the information required to detect, classify, and quantify oil in the marine and coastal environment.

It will require the combined advances in sensor technologies and computer capabilities noted above to gather, integrate, and merge several sources of data into a real-time format, useable by response crews in the field. If this type of information can be made available to response crews in a short enough time frame following a spill incident, then it can be used to lessen the potentially disastrous effects of a major oil spill on the marine ecosystem.

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